MINIATURE, LOW-COST, HIGHLY AUTONOMOUS SPACECRAFT — A FOCUS FOR THE NEW MILLENNIUM

David Collins and Carl Kukkonen,* Technology and Applications Programs Directorate
Jet Propulsion Laboratory (JPL), California Institute of Technology
Pasadena, CA 91109-8099

Samuel Venneri,** Office of Space Access and Technology
National Aeronautics and Space Administration (NASA)
Washington, DC 20546-0001

Abstract

NASA is working aggressively toward greatly reducing the life-cycle costs of planetary, space physics, astrophysics, Earth observing, and communications missions. In order to pursue important programs in space and Earth science and commercial applications of space in the twenty-first century, frequent, affordable missions are required. These are enabled through a fundamental paradigm shift in the ways of doing business and the application and validation of advanced technology. Miniaturization of spacecraft and spacecraft instruments leads to lower mass and greatly reduces launch costs. Use of high-level spacecraft building blocks with low recurring costs simplifies spacecraft design and simulation and, together with advanced manufacturing, assembly, and test, greatly reduces development costs. And making spacecraft highly autonomous greatly reduces operations costs. In addition, measures such as targeting appropriate, focused missions and payloads, minimizing spacecraft power requirements, using low-nuclear or non-nuclear power sources, employing on-board analysis and data compression, and eliminating non-cost-effective redundancy can contribute broadly to reduction in life-cycle costs. This paper expands further on these areas and includes specific example spacecraft design concepts, such as the one illustrated at the right, that are consistent with the vision and approach.

---

* David Collins is Manager of Microspacecraft Systems Technology; Carl Kukkonen is Director of the Center for Space Microelectronics Technology and Manager of the Supercomputing Project,

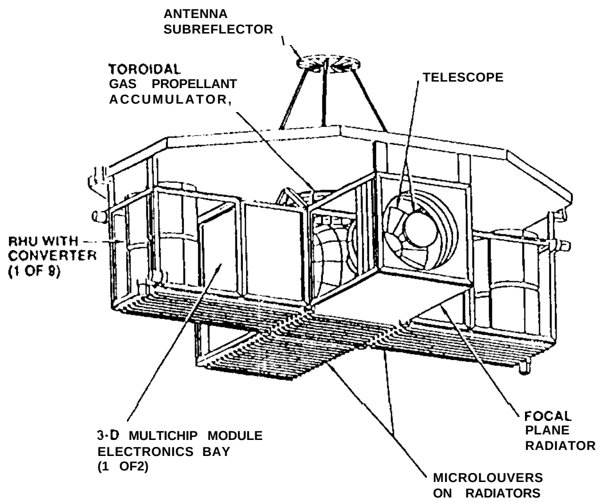
** Samuel Venneri is Director of the Spacecraft Systems Division.

EXAMPLE OUTER SOLAR SYSTEM FLYBY
SPACECRAFT & ASSOCIATED TECHNOLOGY NEEDS

Science: Imaging & Imaging Spectroscopy

Size: 46-cm diameter x 30-cm height

Power: 0.1-15 W Wet Mass: 8.4 kg Uplink: None



Core Building Block Technologies:

Autonomous Control Techniques & Algorithms
High-Capability, Low-Power Digital & Neural Processors
High-Density, Non-Volatile Memories
Compact, Low-Mass, Athermal Optics
Integrated Detection, Processing, & Digital Conversion
High-Efficiency Power Conversion & Compact Switching
High-Efficiency RF Exciters, Modulators, & Amplifiers

Other Key Technologies:

Very Small, Low-Power Inertial Reference Units
High-Energy-Density, Rechargeable Batteries
Efficient, Variable-Emissivity Microradiators
Low-Mass Sensors, Valves, Tanks, MLI, & Structure

Special, Mission-Specific Technologies:

Very Small Isotope Thermoelectric Power Sources
Specialized, On-Board Data Analysis Techniques
Precision Clocks and Timers
Small, Low-Mass, High-Efficiency Antennas
[Optional] Specialized, Low-Power Microinstruments

Background

Spacecraft evolution has generally been driven toward ever-increasing capability and cost. Demands for more and more ambitious and diverse missions and payloads have both limited cost containment options and translated into increasing demands on spacecraft subsystems, increasing spacecraft size and mass, and increasing complexity of spacecraft ground control. Not surprisingly, increasing cost has resulted in increasing risk aversion and attempts to mitigate risk through the use of massive redundancy and fault protection, both of which further increase spacecraft complexity, size, mass, and cost. Another consequence of risk aversion has been considerable reluctance to fly new technology without lengthy and expensive flight qualification. Typically, this has condemned spacecraft to fly less capable and, frequently, less cost-effective technology. For scientific missions beyond Earth orbit, problems have been exacerbated by such factors as increased communication ranges, different (frequently worse) solar ranges and radiation environments, increased difficulty of navigation, and increased requirements on launch energy. Major scientific missions have become so costly and the funding so limited that flights are quite infrequent. This severe limitation in opportunities for space exploration has dampened enthusiasm for participation in the process and constrained the pace of scientific discovery.

A New Direction for NASA

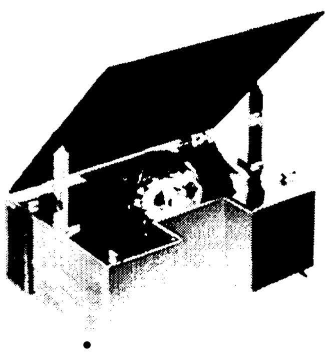
In 1992, Daniel Goldin became the new NASA Administrator under then-President George Bush. His arrival at NASA was preceded by the problems discussed previously, and he was quickly faced with the additional challenges imposed by difficulties in the national economy combined with a major, and ongoing, adjustment of national priorities following the end of the Cold War. His response has been to work vigorously to realign the agency with the new realities and revised priorities while expanding the vision of future space exploration. The slogan "better, faster, cheaper" now permeates NASA; reduction of life-cycle costs is emphasized; and technological innovation has become a primary tool for achieving NASA goals and reaping the "benefits of space for humanity."

A New Generation of Spacecraft

The Jet Propulsion Laboratory, under sponsorship of the NASA Office of Space Access and Technology, is developing concepts for an entirely new kind of spacecraft that inherently embodies the new NASA direction.[1,2,3,4] The purpose of this activity is to help focus technology development on enabling the kind of spacecraft NASA would like to be able to begin flying within the first decade of the new millennium (by 201 O). At JPL the spacecraft are currently referred to as "Second-Generation Microspacecraft," or SGM, to connote both along-term outlook and substantial, not incremental, change from the present. Specifically, the objective for these spacecraft is to greatly reduce flight system, launch, and operations costs while improving mission benefit-to-cost ratios — thus enabling frequent/simultaneous flight of numerous spacecraft and, in the process, providing a catalyst for innovation in technology.

~.preach

The SGM approach to achieve this objective is being carefully refined as studies continue. Basically, it utilizes a number of interrelated cost reduction strategies, and both simplicity and cost-effectiveness are emphasized. Missions are screened for compatibility, resource requirements are minimized (while reasonable margins are maintained), needs for extensive redundancy are circumvented, and volume production of key elements is utilized to reduce spacecraft costs. Spacecraft size, mass, and nuclear material use are minimized to reduce launch costs and further aid spacecraft cost reduction. And spacecraft control autonomy is increased to reduce operations costs. The approach is incorporated in the spacecraft model shown below.[2] (The full-scale model is 33 cm wide.) More details about the approach follow.



Missions. To help reduce demands on spacecraft, launch, and operations resources and their costs, the SGM approach concentrates on an envelope of appropriate, focused missions and payloads. While a broad range of missions and payloads is consistent with the SGM objective and approach and included in this envelope, some classes of missions are not suited for use of SGM, and it would be counterproductive to warp the approach to include them. For example, missions would not be appropriate that inherently require large, fixed, filled apertures; high-mass payloads; extensive spacecraft resources; or considerable commanding from Earth. Even so, some of the SGM approach elements, technologies, and production line products would be expected to be used in these non-SGM missions and contribute to lowering their costs.

Communications. Requirements on the downlink for return of large volumes of data, particularly from long distances from Earth, not only place a heavy burden on the telecommunications subsystem but, indirectly, on other subsystems and systems as well. For example, a large bit-rate capability can require not only a powerful transmitter but also a large antenna, tight pointing control, considerable DC power, and large louver-covered radiators for temperature control. In turn, all these can impact spacecraft size, mass, needed propulsion, and launch requirements. The SGM approach minimizes needed downlink communications through the use of some on-board data analysis and data compression, and, in certain cases, enables more extensive science investigations. Basically, the emphasis is on returning essential information, not large volumes of raw data. This reduces the size, mass, and cost of the telecommunications subsystem, other subsystems, and the spacecraft. In addition, the lower spacecraft mass reduces requirements on the launch vehicle, and lower downlink data volume can reduce tracking station loading and costs. Uplink communication is also minimized (as will be discussed later in this paper), leading to further reductions in requirements on the spacecraft and tracking stations.

Power. **Requirements for power impact not just the power subsystem but other subsystems as well, High power use implies the need** for high-power sources, control, storage, and distribution, and, in addition, high heat conduction and radiation, There are impacts on structure, cabling, temperature control, and propulsion needs, and possibly on the difficulty of attitude control and obtaining adequate magnetic cleanliness. In particular, a need for high-power sources implies, in most cases, the use of large solar arrays, large solar concentrators, or nuclear isotopes. The SGM approach minimizes needed power through the use of low-power electronics and mechanisms, the reduction in communication requirements, the reduction of needed heater use for small spacecraft, and the employment, where reasonable, of short duty cycles. This reduces the size, mass, and cost of the power subsystem, other subsystems, and the spacecraft. In addition, the lower spacecraft mass reduces requirements on the launch vehicle. Expected total SGM load power is approximately 5 to 20 W.

Nuclear Material. **Use** of significant quantities of radioactive material on a spacecraft implies the need for additional safety and security procedures and personnel during spacecraft assembly, transportation, and launch operations. In addition, unless the quantities of nuclear material are very small, an environmental impact analysis (associated primarily with hazards during launch) is usually also required. The SGM approach, taking advantage of lower heating and electrical power generation needs, uses only low-nuclear or non-nuclear energy sources. This reduces the spacecraft safety and security costs and the launch environmental impact assessment or analysis cost.

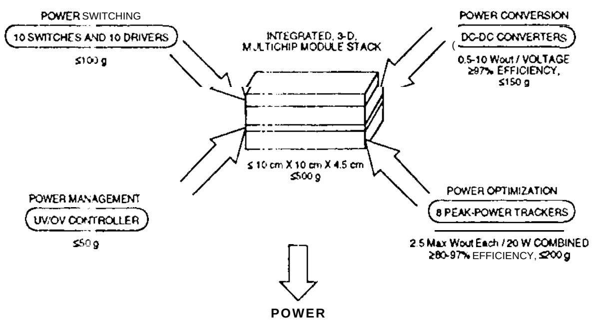
Size and Mass. Large size and mass of spacecraft elements contribute to large propulsion subsystem and structure sizes and masses and, of course, to large overall spacecraft size and mass. The result is that large assembly and test facilities are necessary, spacecraft handling and transportation are difficult, and substantial launch capability is required. Spacecraft size and mass minimization in the SGM approach is based primarily on the reduction in spacecraft resource requirements, miniaturization of spacecraft elements, and correspondingly lower requirements on propulsion and structure. In the launch phase, the size and mass reductions allow use of smaller launch vehicles, flight of many spacecraft per vehicle, and launch of spacecraft as secondary payloads. For example, vehicles that launch other payloads into Earth orbit maybe able to inexpensively carry an SGM as well. The SGM can also be placed in Earth orbit or, if it carries its own, small propulsion stage, sent elsewhere. Another advantage of reduced spacecraft mass is that, for a given launch vehicle, some post-launch trip times can be reduced — thus decreasing risk and operations costs. Expected SGM size and mass are, respectively, approximately 0.3 to 0.6 m in the longest dimension in the launch configuration and approximately 3 to 12 kg. In some cases, it may be acceptable for spacecraft elements to deploy to larger dimensions after launch, but in each case at least the impacts on spacecraft control, reliability, complexity, and cost need to be assessed.

Redundance. The use of extensive block redundancy and associated, sophisticated fault protection algorithms to guard investments in expensive spacecraft and missions has in itself contributed to those high costs as well as to overall spacecraft size, mass, and complexity. With few exceptions, the SGM approach, based on the lower costs that are at risk, eliminates this duplication of much of the spacecraft and reduces spacecraft size, mass, complexity, and cost.

Parts. The same, understandable risk aversion that has led to extensive redundancy has also resulted in demands for particularly high-reliability parts with special qualification and screening programs. Use of these much higher cost parts both directly and indirectly increases spacecraft costs. For example, indirect cost increases result from restrictions on design implementation options stemming from the limited range of available parts. Another problem frequently introduced by the use of these parts is increased lead-time requirements on parts orders. Although the SGM approach does not circumvent the need for reliable parts, reduction in the mission investments that are at risk widens the range of parts that are acceptable — helping to lower spacecraft costs and shorten schedules.

Production. Although there has been limited production of some Earth satellites, particularly communications satellites, only one or two of a spacecraft of a given design for use beyond Earth orbit have typically been produced. The reasons for this include both the high cost and specialized nature of many space missions. Even if recurring costs could be cut substantially through production of a large number of spacecraft, replication of only a single spacecraft type is certainly not the answer; the spacecraft would be too restricted in the missions they could perform. Instead, the SGM approach is to concentrate production one step down from the spacecraft system level. This is accomplished by having all spacecraft implement most of their functionality using subsets of a small number of standardized, production “core building blocks.” This maintains flexibility in the spacecraft types that can be built while still allowing large reduction in recurring costs. Of course, concentrating production at even lower levels of spacecraft functionality would allow still more flexibility, but the savings in recurring **costs would diminish.** An example of one building block concept is illustrated below.[3]

POWER ELECTRONICS
BUILDING BLOCK



The blocks are each designed for high capability and flexibility of use, manufactured-in quality and reliability, and low recurring cost. They have standardized interfaces and, in some cases, options for modular additions and deletions (but not so many options that cost savings from production are jeopardized). For example, in missions that do not use solar arrays, the peak-power tracking module can be deleted from the building block shown above. Another feature of the blocks is that most required electrical interconnection in a spacecraft is efficiently implemented within the production building blocks, leaving little additional electrical interconnection required during spacecraft assembly. In addition to serving NASA needs, use of certain building blocks in other government, industrial, and commercial applications (including some non-space applications) is expected. Production rates for each block and the associated spacecraft cost savings depend on demand. There are at least four core building block types including Information Processing and Control, Optics and Focal Plane, Power Electronics, and Telecommunications Electronics. In the latter case, there maynot be just one design but two or three different versions for use at different frequencies.

In addition to this assembly-line production of large portions of the spacecraft, to further reduce costs, limitations are applied to the range of differences that are allowed in the implementations of spacecraft for similar missions. The SGM designs fall into a number of different mission classes, but within each class the mission characteristics and payloads are similar, and little change is necessary from one mission to the next.

Design, Assembly, and Testing. Just asthe customized nature of many spacecraft has been a factor in preventing assembly-line production and associated cost savings, it has contributed to high costs of design, assembly, and testing. In the SGM approach, most of the functionality of each spacecraft is preexisting at the beginning of the design process in the form of the building blocks. The building blocks are well characterized and simulations of them in design tools further aid the design process. Another aid to design simplification is the use of general design guidelines that apply to all SGM, with more specialized supplements that apply to each mission class. The focus of these is reasonable simplification of the designs and standardization of the design process. Spacecraft assembly is also greatly simplified and speeded by using the building blocks and is further aided by having stockpiles of parts that are common to many SGM. (Lead times for most spacecraft hardware are near zero in this "pipeline" approach.) Spacecraft testing is speeded by the simplified nature of the designs and their commonality. It gains still greater efficiency by utilizing automated test equipment that incorporates preexisting knowledge of spacecraft design guidelines and building block characteristics and requirements. Most necessary troubleshooting and repair are also simplified and can be expedited because replacement building blocks can be quickly substituted for those in the spacecraft that are being tested.

Uplink. Typically, the uplink process, i.e., commanding the spacecraft from Earth, is responsible for the majority of mission operations costs. In the SGM approach, extensive spacecraft autonomy is utilized to greatly reduce or eliminate these costs. Highly autonomous spacecraft are used for some complex and critical missions, and fully autonomous spacecraft are used for most of the others. In this latter case, the spacecraft command receivers and associated hardware and software can be eliminated along with the uplink process. Although doing this would reduce flexibility of response to certain problems and opportunities in flight, it would also assure zero expenditures on an uplink process to deal with them, and it would reduce other resource needs and costs as well. There is no inherent requirement, however, that SGM capable of full autonomy fly without command receivers. More accurately, those spacecraft are "uplink optional"; that is, a receiver and limited uplink process can be added if there is sufficient funding, justification, and spacecraft power, volume, and mass. An additional benefit of high or full spacecraft autonomy is that in many instances it allows science return superior to that which would be possible if Earth had to be in the command loop. This is because delays in decisions are eliminated that otherwise would result from the "round-trip-light-time" of the transmissions to and from Earth.

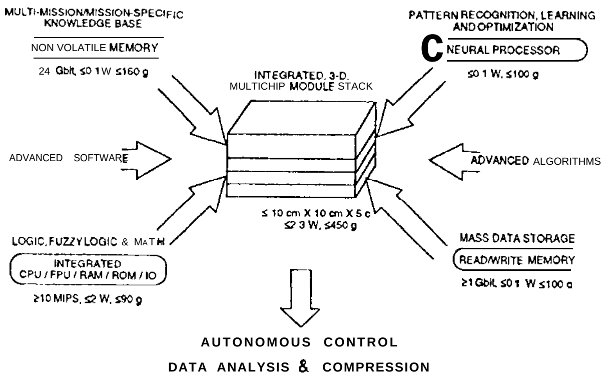
Technology

Needed technologies include both those that support the core building blocks and those that support other elements that are common to nearly all SGM but do not happen to be in the building blocks. In addition, technologies are needed that support certain, mission-specific objectives. These three lists are still evolving and being refined, but it is thought that all needed technologies either currently exist or are reasonable extrapolations of current research, if that research receives proper direction and adequate support. Example, high-level descriptions of needed technologies are included below.

Core Building Block Technologies. Within the building blocks, needs for miniaturized, low-power electronics are pervasive. To simplify the listings, however, these particular needs are not separately identified. Also, elements of the building blocks that are required but do not have significant technology development needs are not discussed.

Information Processing and Control. This building block provides the “brain” function for the spacecraft. In one possible implementation,[3] as shown below, resource utilization is <2.3 W, ≤ 10 cm x 10 cm x 5 cm, and ≤450 g.

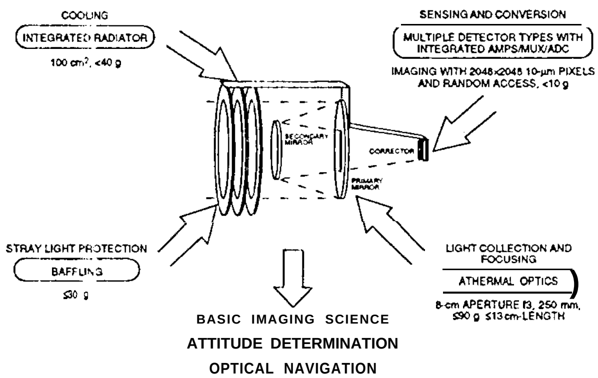
INFORMATION PROCESSING AND CONTROL
BUILDING BLOCK



Technology needs include: high-capability, low-power microcomputers; efficient, high-capability neural processors; high-density, non-volatile memories; and autonomous control techniques. Digital processing provides logic, fuzzy logic, and mathematical functions. The eventual implementation of the digital processing may utilize a single processor or a combination of processors selected from complex and reduced instruction set central processing units, floating point units, digital signal processors, and parallel processors. In this area in particular, the technology emphasis is on low power consumption, since it is thought high computational capabilities will be more easily achieved. Neural processing provides pattern recognition, optimization, and learning functions. This processing may be implemented with one or more processor types with either local or remote weight storage. Non-volatile memory (in a read-only knowledge base) provides the information to the spacecraft that it needs to carry out its mission. In addition to providing quickly accessible data, in spacecraft implementations with full autonomy and no uplink, the information stored in the memory replaces that which otherwise could be provided from Earth. Autonomous control, as well as mission-specific data analysis, is provided by this building block and is one area in the SGM approach in which demands on spacecraft resources are actually increased. This is justified by a combination of the resource and cost savings in mission operations and communications as well as by benefits in efficiency and capability that result from in situ control and analysis. The expectation that sufficient advancement in autonomy can be realized within the next 10 – 15 years is based on the growth of machine intelligence research and the extremely rapid increases in machine computational capability and concurrent reductions in power, size, mass, and cost.

Optics and Focal Plane. This building block provides the fundamental optical sensing functions that are needed by most SGM. These support attitude determination, autonomous navigation, basic science imaging, and, possibly, imaging spectroscopy. An important reason for integrating these sensing functions is that the space available for needed apertures and optics begins to rapidly decrease as spacecraft become smaller and approach the SGM size regime. (One possible way to partially get around this problem is to use apertures and optics that expand after launch, but complexity, reliability, cost, and other impacts would need to be considered.) The current implementation concept for the building block is shown below.[3] It uses an aperture and optics with fixed sizes, and its resource utilization is ≤0.3 W, < 10 cm x 10 cm x 16 cm, and <170 g.

OPTICS AND FOCAL PLANE
BUILDING BLOCK



Technology needs include: compact, low-mass, athermal optics; integrated, multi-functional sensing; and on-focal-plane amplification, multiplexing, and analog/digital conversion.

Power Electronics. Power control, optimization, conversion, and switching are provided in this building block. An illustration of one possible implementation is shown earlier in this paper in the section on production. In that concept,[3] resource utilization is < 10 cm x 10 cm x 5 cm and ≤500 g. Technology needs include: high-efficiency peak-power tracking; high-efficiency power conversion; and compact power switching.

Telecommunications Electronics. Unlike the other core building blocks, there are multiple versions of the telecommunications electronics: one for X-band, one for Ka-band, and one for optical communications. In current implementation concepts,[3] these range in resource utilization from ≈5 W, < 10 cm x 10 cm x 2 cm, and <400 gfor optical modulation and beam steering control to ≤8 W, ≤ 10 cm x 10 cm x 3.5 cm, and <600 g for Ka-band excitation, modulation, and amplification (for 1.5-W RF output). Technology needs for the radio communication options include: low-power exciters and modulators and high-efficiency RF power amplifiers. Technology needs for the optical communication option are low-power modulation and beam steering.

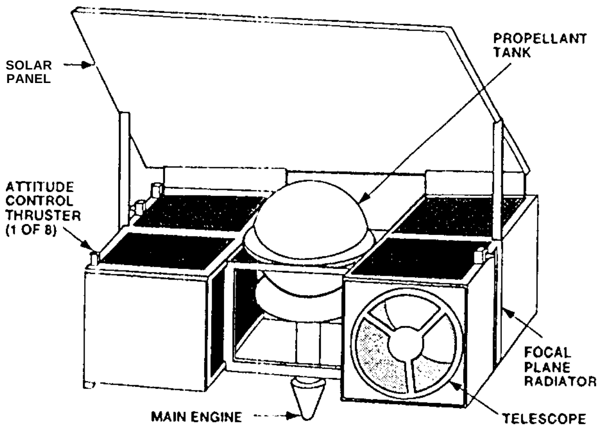
Common Element Technologies. Other technologies that are needed to support nearly all missions include: very small, low-power, inertial reference units; high-energy-density, rechargeable batteries; high-heat-conductivity materials; variable-emissivity microradiators; low-mass insulation; low-mass, low-power microvalves; low-mass pressure transducers; low-mass propellant tanks; and low-mass structure.

Mission-Specific Element Technologies. A partial list of technologies that are needed to support particular mission classes, but not others, includes: low-mass, high-efficiency solar arrays; specialized, low-power micro instruments; low-mass, high-specific-impulse propulsion stages; small, low-mass, high-efficiency antennas; high-specific-energy primary batteries; altitude/velocity-vector microsensors; stable, low-solar-absorptance / high-emissivity surfaces; very small isotope thermoelectric power sources; precision clocks and timers; and specialized, on-board data analysis techniques and algorithms.

Example Spacecraft Concepts

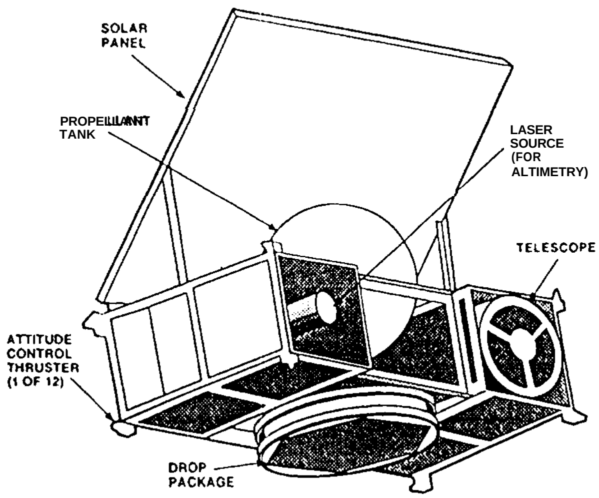
Initial concepts for four different spacecraft that each support a different class of mission are briefly described below. These concepts are all consistent with the SGM objectives and approach and utilize the core building blocks and common elements discussed earlier. Additional areas of commonality shared by all the spacecraft include: simple frame structure, monopropellant or cold gas propulsion, use of <10 power switches, O - 2 deployments, no pyrotechnic control unit, and no command uplink/receiver.

Near-Earth Object Flyby Spacecraft.[1]



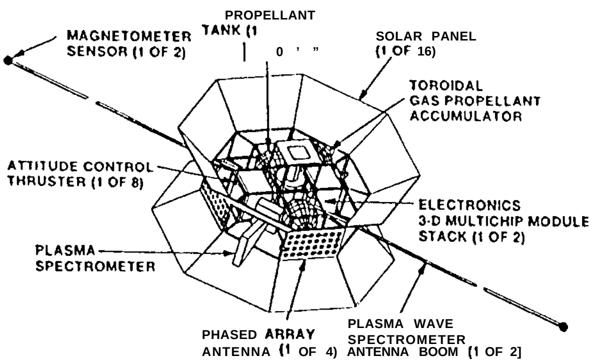
The spacecraft autonomously provides imaging and imaging spectroscopy of a near-Earth asteroid or comet for spacecraft solar ranges of 0.8 to 1.2 AU and Earth ranges up to 1.6 AU. Estimated spacecraft wet mass, launch configuration size, and load power are, respectively, 5.5 kg, 20 cm x 33 cm x 27 cm, and 5 to 13 W (depending on transmitter state: off or on).

Near-Earth Object Rendezvous Spacecraft with Drop Package.[5]



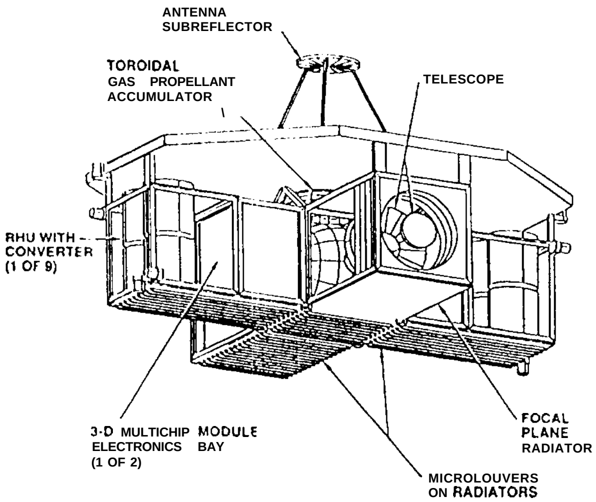
The spacecraft autonomously provides full-body imaging and imaging spectroscopy of a near-Earth asteroid or comet as well as in situ alpha/proton/x-ray (APX) measurement and gamma-ray spectroscopy (GRS) . After mapping the object, the spacecraft moves closer along a radial toward the most illuminated pole of rotation, releases the surface drop package, backs away, and, after some data reduction, relays the in situ measurement data to Earth. (As with the other example spacecraft, no uplink is used, but this is more of a challenge in this mission class than in the other examples.) Estimated spacecraft wet mass, launch configuration size, and load power are, respectively, 7 kg, 20 cm x 35 cm x 33 cm, and 6 to 13 W (depending on transmitter state: off or on). Augmentation with a miniature propulsion stage is required (but not shown in the figure), which increases the launch mass and payload volume. Spacecraft separation from the stage is shortly after the final rendezvous burn is complete.

Space Physics Fields and Particles Spacecraft.[6]



The spacecraft autonomously provides magnetic, plasma, and plasma wave analysis of the environment for spacecraft solar ranges of 0.5 to 1.2 AU and Earth ranges up to **1.7 AU.** The spacecraft also retains imaging and imaging spectroscopy capabilities. Unlike the other example SGM, this spacecraft is designed to be capable of four different mission classes without change in spacecraft hardware. These mission classes include enhanced near-Earth object flyby, multipoint magnetospheric measurement in Earth orbit, solar warning from the L1 point, and solar early warning precursor missions at 0.5 AU solar range. Estimated spacecraft wet mass, launch configuration size, and load power are, respectively, 12 kg, 65-cm diameter x 30-cm height, and 7 to 19 W (depending on operating state).

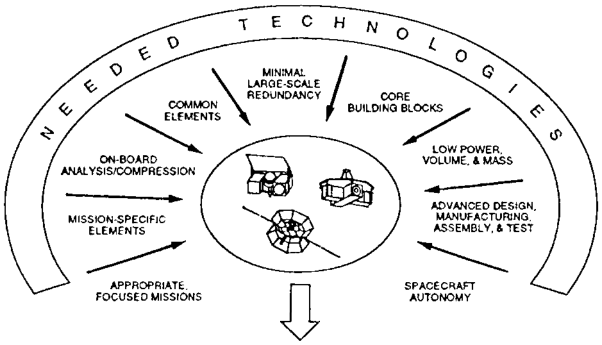
Outer Solar System Flyby Spacecraft.[7]



The spacecraft autonomously provides imaging and imaging spectroscopy of objects in the outer solar system for spacecraft solar ranges of 3 to 39 AU and Earth ranges up to 38 AU. Estimated spacecraft wet mass, launch configuration size, and load power are, respectively, 8.4 kg, 46-cm diameter x 30-cm height, and 0.1 to 15 W (depending on operating state). In this mass regime, missions to the outer solar system with relatively short trip times appear possible using small launch vehicles with appropriate upper stages. Unlike the other example SGM, this spacecraft spends most of its time in cruise in a “hibernation” state in which only a clock/timer is operating and electrical power is being stored, Also, since communications rates are low and operating periods are limited, more on-board data analysis is utilized, particularly for long-range targets, than in the mission classes discussed earlier.

Summary

Concepts are being developed that help focus technology development on enabling the kind of spacecraft NASA would like to be able to begin flying within the first decade of the new millennium. The objective for these spacecraft is to greatly reduce flight system, launch, and operations costs while improving mission benefit-to-cost ratios — thus enabling frequent/simultaneous flight of numerous spacecraft and, in the process, providing a catalyst for innovation in technology. The approach described in this paper to meet this objective utilizes innovative system design and new technology to minimize cost drivers including communications, power, nuclear material, redundancy, size and mass, and uplink commanding. It employs production and advanced design, assembly, and testing methods to minimize recurring costs, and it selects missions and payloads that are compatible with the cost-reduction objective and approach. The combination of developing the needed technologies and implementing this approach can meet the objective and enable miniature, low-cost, highly autonomous spacecraft for missions in the new millennium.



LOW LIFE-CYCLE COST
HIGHER RETURN PER DOLLAR
FREQUENT FLIGHT
INNOVATION IN TECHNOLOGY

Acknowledgements

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The authors wish to thank the numerous individuals at the Jet Propulsion Laboratory who have contributed to this research.

References

[1]Collins, D. H., et al., *Year-End Status Report: A Second Generation Microspacecraft Vision and Conceptual Design,* internal document D-1 1185, Rev. A, Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, Oct. 1993.

[2]Collins, D., "Second-Generation Microspacecraft for the Next Decade," *Space Microelectronics,* Issue *6,* document JPL **410-25-6 3/95,** Center for Space Microelectronics Technology, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, spring 1995, pp. 32–41 .

[3]Collins, D. H., "Second Generation Microspacecraft –- A Long-Range Focus for Technology Development," *Workshop on Future NASA Miniature Spacecraft Technology,* Vol. 1, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, Feb. 1995.

[4]Collins, D. H., "Second Generation Microspacecraft," to be published in *Monograph of Future Aeronautical and Space Systems,* AIAA Series — F'regress in Astronautics and Aeronautics.

[5]Muller, L., et al., "Near-Earth Object Rendezvous with a Surface Drop Package," *Second Generation Microspacecraft Final Reports for 7994,* internal document D-1 2645, Rev. A, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 1995, pp. **91-161.**

[6]Collins, D. H., Horvath, J. C., et al., "Space Physics Fields and Particles Mission Class Spacecraft," *Second Generation Microspacecraft Fins/ Reports for 7994,* internal document D-12645, Rev. A, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 1995, pp. 59–89.

[7]Collins, D. H., et al., "Outer Solar System Flyby," *Second Generation Microspacecraft Final Reports for 7994,* internal document D-1 2645, Rev. A, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 1995, pp. 27--57.